Extinction of Bluff-Body Stabilized Diffusion Flames

Fumiaki Takahashi* and W. John Schmoll
University of Dayton Research Institute
300 College Park, Dayton, Ohio 45469

Vincent M. Belovich
Air Force Research Laboratory
Wright-Patterson Air Force Base, Ohio 45433

The extinction limits of a methane diffusion flame stabilized behind a backward-facing step in a small-scale wind tunnel were measured by injecting a fire-extinguishing agent (halon 1301) into the airflow. As the mean air velocity was increased, two distinct flame stabilization regimes were observed: rim-attached and wake-stabilized flames. For a fixed mean air velocity, the agent concentrations at extinction varied inversely with the agent injection period. As a result, the agent mass required to suppress the flame was nearly constant for a given air velocity, independent of the agent concentration and injection time. The critical agent mass increased with the mean air velocity.

Introduction

Fires in the aircraft engine nacelle, which encases the engine compressor, combustors and turbine, can be stabilized by a recirculation zone formed behind obstacles (clutters and tubes, etc.) and in cavities under ventilated conditions [1-10]. The fuel sources are leaking jet-fuel and hydraulic-fluid lines that can feed the fire in the form of a spray, puddle, or pool. Similar conditions may exist in fires in aircraft dry bays, ships, or land combat vehicle engine compartments. Suppression occurs when a critical concentration of agent is transported to the fire. After the fire is extinguished, re-ignition may occur as the fuel-air mixture makes contact with hot metal surfaces or sparks from damaged electrical circuits.

Because of its superior effectiveness, halon 1301 (bromotrifluoromethane, CF_3Br) has been used as a fire-extinguishing agent to protect aircraft engine nacelles and other compartments. As halon 1301 is replaced with a possibly less effective agent, the amount of replacement agent required for suppression over a range of operating conditions must be determined. Hence, it is not clearly known whether or not the flame extinguishing data [7, 11-13] using conventional methods such as a cup burner can effectively characterize bluff-body stabilized flames.

The broad objectives of this study are as follows:

(1) Determine difficult-to-extinguish cases by a parametric investigation using combinations of given geometric elements and experimental conditions. The parameters to be considered are (a) clutter configuration (backward-facing step, buffle plate, J-flange, cavity, and blockage ratio), (b) fuel and injection characteristics (fuel type: methane, JP-8, 83282 hydraulic fluid; temperature, injector type, location, angle, spray, puddle, or pool), (c) air flow characteristics (velocity and temperature), (d) hot surface (roughness and temperature), and (e) suppression agents (agent type: CF_3Br, CF_3I, C_2HF_5 [HFC-125], C_3HF_7 [HFC-227ea], etc.; temperature, supply vessel pressure and injection period).

(2) Gain a better understanding of the fundamental mechanisms of flame stabilization and identify the critical parameters that are important to suppressing bluff-body stabilized flames. Representative cases will be studied in detail using planar flow visualization, schlieren method, and two-color particle image velocimetry.

(3) Develop a phenomenological model that can be integrated into computational fluid dynamics models for predicting bluff-body stabilized fires and their suppression.

In this paper, the initial experimental results are reported on the extinction limits of a methane flame stabilized behind a backward-facing step using halon 1301 as the baseline suppression agent.

Experimental Techniques

Figure 1 shows a schematic of the experimental apparatus for the model-fire suppression study. The apparatus consists of the fuel, air and agent supply systems, a horizontal small-scale wind tunnel, and a combustion product scrubber. Methane issues upward at a mean velocity of 0.7 cm/s from a porous plate (150 × 150 × 12.7-mm thickness, stainless steel) placed downstream of a backward-facing step (64-mm height) in the test section (154 × 154-mm^2 cross-section, 77-cm length). The airflow is regulated by passing through honeycombs,

* Corresponding author
Proceedings of the 1998 Technical Meeting of the Central States Section of the Combustion Institute

a diffuser, mesh screens (#100), a contraction nozzle, and a turbulence generating perforated plate (33% opening, 2.4 mm-dia. holes). The turbulence level in the wind tunnel is typically ~6%. The mean air velocity is calculated by dividing the volumetric flow rate by the cross-sectional area of the air passage above the step. The results for three different mean air velocities (2.5, 5, and 12.5 m/s) are reported here.

The agent supply system, which is similar to that of Hamins et al. [7, 8], consists of a (liquid) agent reservoir (3.8 l), two connected gaseous agent storage vessels (38 l each), and a computer-controlled solenoid valve. The gaseous agent was injected impulsively into the air ~1 m upstream of the flame. Uniform agent dispersion into the airstream was achieved by injecting the agent radially into a reduced diameter (108 mm) section of the air passage through 16 6.4-mm-dia. holes in a 25.4-mm-dia. closed-end tube. The mesh screens and a perforated plate downstream ensure complete agent-air mixing prior to entering the flame zone. The storage volume, including two pressure vessels and associated plumbing, is 79.9 l. The agent temperature and pressure in the second storage vessel are measured with a type-T thermocouple and a pressure transducer. The amount of injected agent is controlled by varying the initial pressure and the time period that the valve is open and determined from the difference between the initial and final pressures in the storage vessel using the ideal-gas equation of state. The mean volumetric agent concentration is determined by dividing the mean agent flow rate (volume/injection period) by the airflow rate.

The cyclone-type scrubber is attached to the exit of the test section to remove acidic gases (HF) by water sprays from eight pressure-swirl atomizers on the top plate. The gases are exhausted through the central tube and the water is collected in a drain tank. An air-driven ejector is attached to the scrubber exit to reduce the backpressure and adjust the pressure of the test section to atmospheric.

The extinction limit experiment is conducted as follows. First, a stable flame is established for a fixed mean airflow velocity, and then the agent is injected for a particular storage vessel pressure and an injection period. The experiment is repeated until the flame is extinguished, or not extinguished, three times consecutively to determine the extinction or no-extinction condition. If the extinction (or no-extinction) condition is confirmed, the injection period is decreased (or increased) step-wise to determine the extinction limit.

Results and Discussion

Figure 2 shows a schematic of the flames. Two distinct flame stabilization regimes were observed: rim-attached and wake. At low mean air velocities (<2.8 m/s), a wrinkled laminar diffusion flame attached to the edges of the backward-facing step. There existed a short (~2 cm) blue flame zone, with a dark space (~1 mm) between the flame base and the rim, and a trailing long (~50 cm) yellow flame, typical of hydrocarbon diffusion flames. On the other hand, at high mean air velocities (>8 m/s), a turbulent blue flame was stabilized approximately 1 cm downstream of the rim and yellowish flame zones were sporadically formed in the wake of the step. The flow in the wake appeared to be three-dimensional with a main recirculation zone in the central region of the wind tunnel, outward reverse flows near the side windows, and a small corner vortex in the inner corner of the step. At moderate mean air velocities between these two flame stabilization regimes, a highly unstationary transitional flame was observed with the flame base moving back and forth (5-15 cm from the step).

Figure 3 shows the agent injection period at extinction as a function of the initial pressure of the agent storage vessel. At a fixed mean air velocity, the agent injection period at extinction decreased monotonically as the initial storage vessel pressure was increased. A longer injection period was needed to extinguish the flame at higher air velocities for a given initial vessel pressure. The actual agent mass released at a given vessel pressure was dependent on the injection system used. Therefore, the results are re-plotted against the mean volumetric agent concentration in Figure 4. For the mean air velocities of 2.5 m/s and 5 m/s, the agent period vs. concentration curves are nearly coincident. For the mean air velocity of 12.5 m/s, the no-extinction ranges are much narrower.

For all mean air velocities and low agent concentrations (<3 %), the flame could not be extinguished even at long injection times. This agent concentration threshold is roughly consistent with the result obtained using a cup burner [7]. Furthermore, there existed a minimum injection period (~0.1 s), below which the flame could not be extinguished even at high agent concentrations. This injection period threshold may relate to the residence time in the wake behind the step.

The extinction of diffusion flames is generally explained [14] by the Damköhler number ($Da = \tau_r/\tau_c$, τ_c: the chemical time and τ_r: the flow or diffusion time). There exists a critical value of the Damköhler number below which extinction occurs. Increasing the agent concentration or injection period enhances chemical inhibition (and heat losses), thus increases the chemical time, and decreases Da. On the other hand, increasing the air velocity decreases the flow time and, in turn, Da. Therefore, as these parameters were increased, the no-extinction region in Fig. 4 narrowed.

Figure 5 shows a re-plot of the data, in which the critical total agent mass required to extinguish the flame is plotted as a function of the initial storage vessel pressure. Interestingly, the critical total agent mass was nearly constant for a given mean air velocity, although there were considerable scatters mainly due to a limited number of repetitions at each data point. The constancy suggests that the total agent mass relates to the chemical time. The results appear to be consistent with the fact that the chemical time should be constant for a constant flow time (inverse of the velocity) at the extinction condition, i.e., the critical Damköhler number.

Figure 6 shows the critical total agent mass at extinction plotted against the mean air velocity. As the mean air velocity was increased, the critical mass increased proportionally and then tended to level off, thus requiring less agent relative to the air mass flow.

Conclusions

The initial results of the extinction limits of methane diffusion flames stabilized by a backward-facing step in an airstream were reported using halon 1301. Two distinct regimes of flame stabilization were observed: rim-attached wrinkled laminar flame and wake-stabilized turbulent flame. Because the rim-attached flame detached and burned in the wake as soon as the agent was injected for all agent concentrations and injection periods tested, the flame suppression phenomena can be treated on the same basis with the wake flames. In general, the injection period at extinction decreased as the agent concentration was increased. The total agent mass at extinction was nearly constant at a given mean air velocity, independent of the agent concentration and injection period. The critical total agent mass at extinction increased linearly with the air velocity and tended to level off.

Acknowledgment

This work was supported by the U. S. Air Force Research Laboratory, Propulsion Directorate, Propulsion Sciences and Advanced Concept Division, Wright-Patterson Air Force Base, Ohio, under Contract No. F33615-97-C-2719 (Technical Monitor: C. W. Frayne).

References

1. Hirst, R., Farenden, P. J., and Simmons, R. F., "The Extinction of Fires in Aircraft Jet Engines—Part I, Small-Scale Simulation of Fires," *Fire Technology* 12: 266-289 (1976).
2. Hirst, R., Farenden, P. J., and Simmons, R. F., "The Extinction of Fires in Aircraft Jet Engines—Part II, Full-Scale Fire Tests," *Fire Technology* 13: 59-67 (1977).
3. Dyer, J. H., Marjoram, M. J., and Simmons, R. F., "The Extinction of Fires in Aircraft Jet Engines—Part III, Extinction of Fires at Low Airflows," *Fire Technology* 13: 126-138 (1977).
4. Dyer, J. H., Marjoram, M. J., and Simmons, R. F., "The Extinction of Fires in Aircraft Jet Engines—Part IV, Extinction of Fires by Sprays of Bromochlorodifluoromethane," *Fire Technology* 13: 223-230 (1977).
5. Moussa, N. A., "Effects of Clutter on Performance of Fire Suppression Agents in Aircraft Dry Bays and Engine Nacelles," Report prepared for Booz, Allen and Hamilton, Dayton, Ohio, April 1994.
6. Grosshandler, W. L., Gann, R. G., and Pitts, W. M., "Introduction," *Evaluation of Alternative In-Flight Fire Suppressants for Full-Scale Testing in Simulated Aircraft Engine Nacelles and Dry Bay Bays* (Grosshandler, W. L., Gann, R. G., and Pitts, W. M., eds.), *NIST* SP 861, National Institute of Standards and Technology, April 1994, pp. 1-12.
7. Hamins, A., Gmurczyk, G., Grosshandler, W., Rehwoldt, R. G., Vazquez, I., Cleary, T., Presser, C., and Seshadri, K., "Flame Suppression Effectiveness," *ibid.*, April 1994, pp. 345-465.
8. Hamins, A., Cleary, T., Borthwick, P., Gorchkov, N., McGrattan, K., Forney, G., Grosshandler, W., Presser, C., and Melton, L., "Suppression of Engine Nacelle Fires," *Fire Suppression System Performance of Alternative Agents in Aircraft Engine and Dry Bay Laboratory Simulations* (R. G. Gann, ed.), *NIST* SP 890: Vol. II, National Institute of Standards and Technology, Nov. 1995, pp.1-199.
9. Hamins, A., Presser, C., and Melton, L., "Suppression of a Baffle-Stabilized Spray Flame by Halogenated Agents," *Twenty-Sixth Symposium (International) on Combustion,* The Combustion Institute, 1996, pp. 1413-1420.
10. Gran, I. R., and Magnussen, B. F., "A Numerical Study of a Bluff-Body Stabilized Diffusion Flame. Part 1. Influence of Turbulence Modeling and Boundary Conditions," *Combustion Science and Technology* 119: 171-190 (1996).
11. Saso, Y., Saito, N., Liao, C., and Ogawa, Y., "Extinction of Counterflow Diffusion Flames with Halon Replacements," *Fire Safety Journal* 26: 303-326 (1996).
12. Liao, C., Saito, N., Saso, Y., and Ogawa, Y., "Flammability Limits of Combustible Gases and Vapors Measured by a Tubular Flame Method," *Fire Safety Journal* 27: 49-68 (1996).
13. Saito, N., Saso, Y., Liao, C., and Ogawa, Y., "Flammability Peak Concentration of Halon Replacements and Their Function as Fire Suppressants," ACS Symposium Series No. 611, *Halon Replacements: Technology and Science* (A. W. Miziolek and W. Tsang, eds.), The American Chemical Society, 1995, pp. 243-257.
14. Williams, F. A., "A Unified View of Fire Suppression," *Journal of Fire & Flammability* 5: 54-63 (1974).

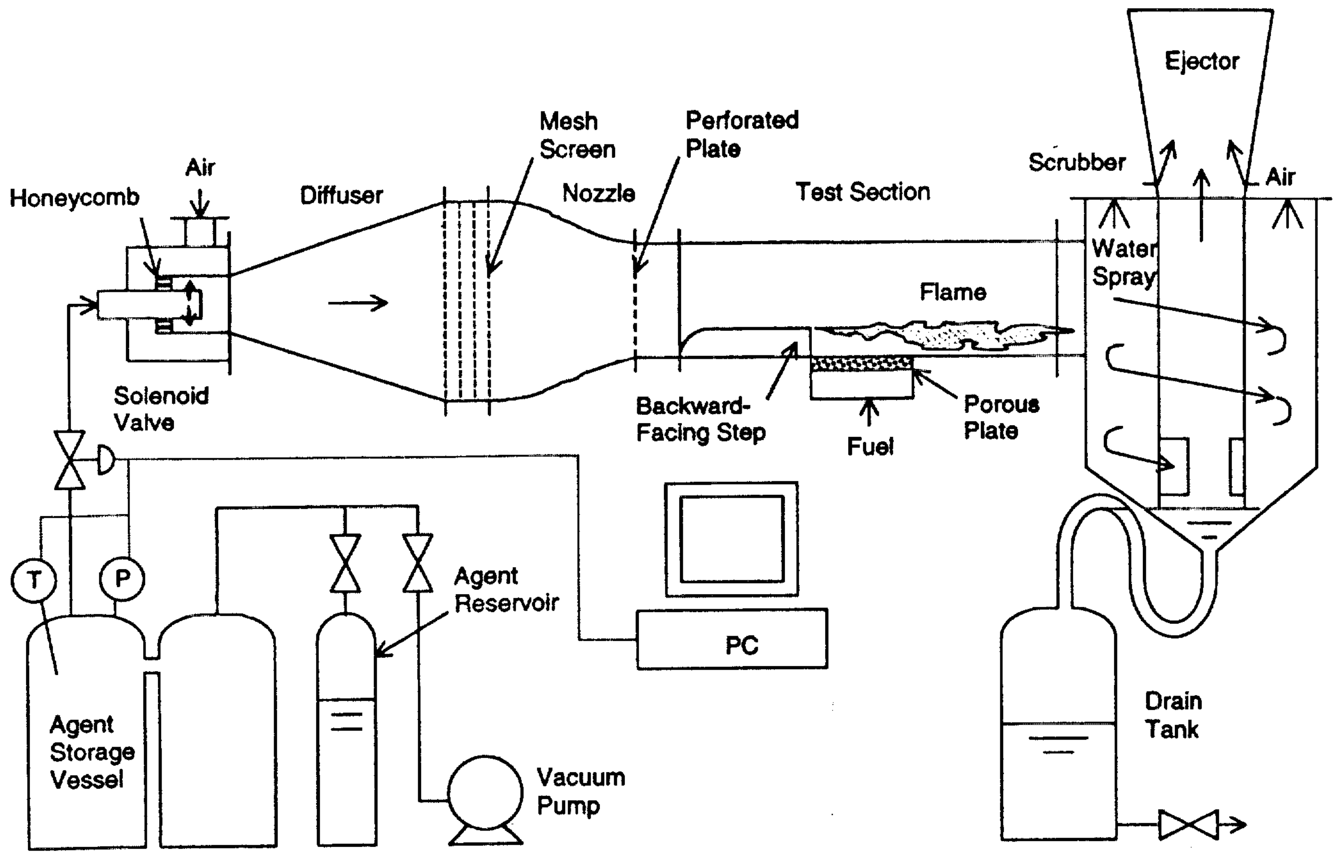

Fig. 1 Experimental apparatus.

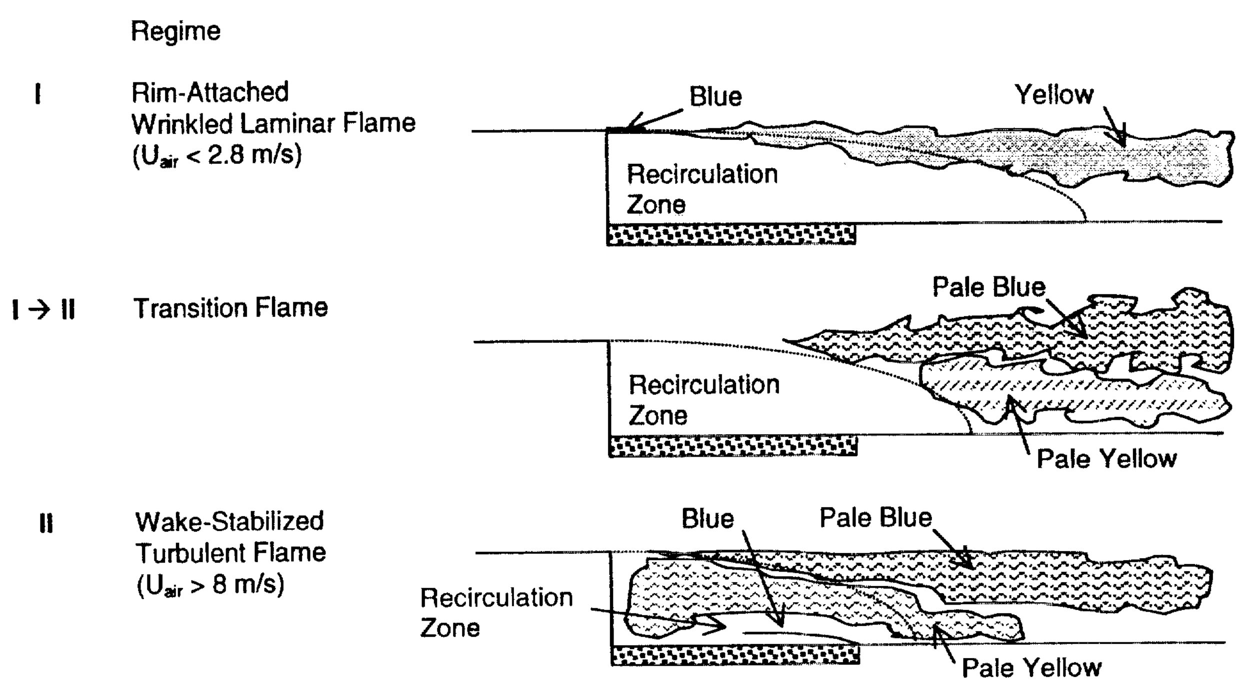

Fig. 2 Flame stabilization regimes.

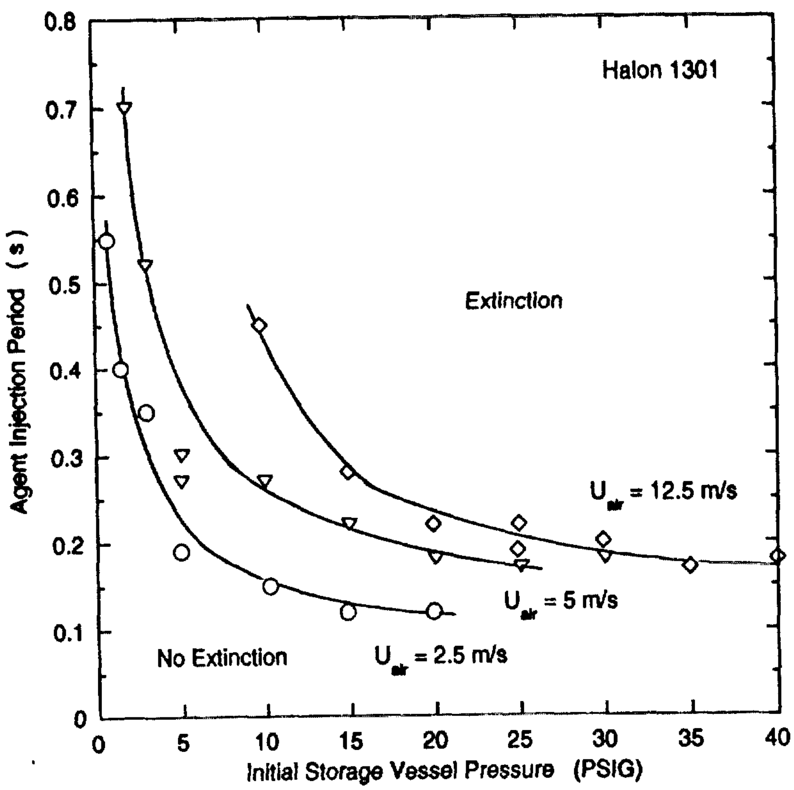

Fig. 3 Extinction limits of step-stabilized methane flames: agent injection period vs. initial vessel pressure.

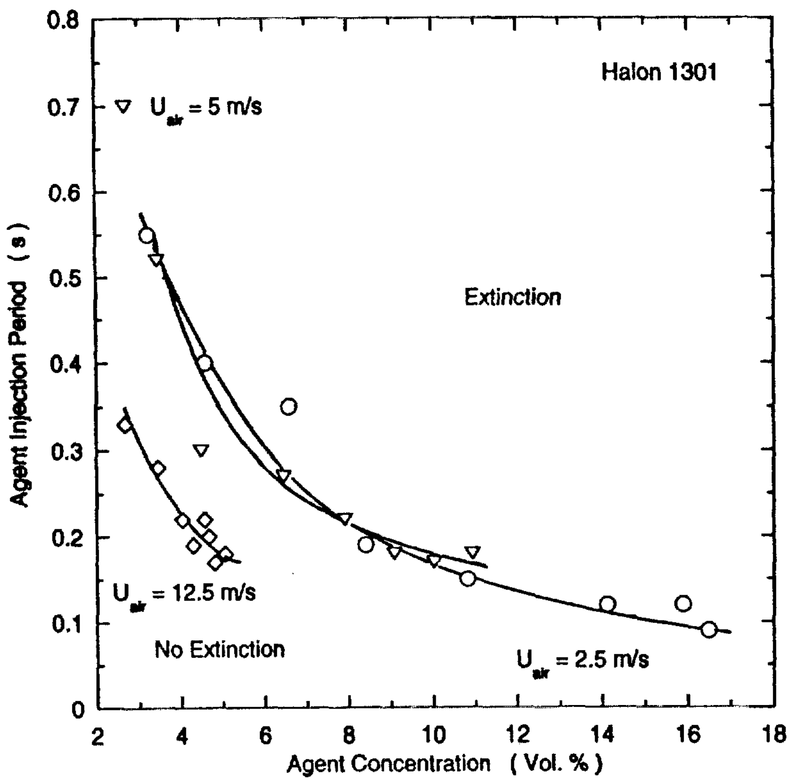

Fig. 4 Extinction limits of step-stabilized methane flames: agent injection period vs. volumetric concentration.

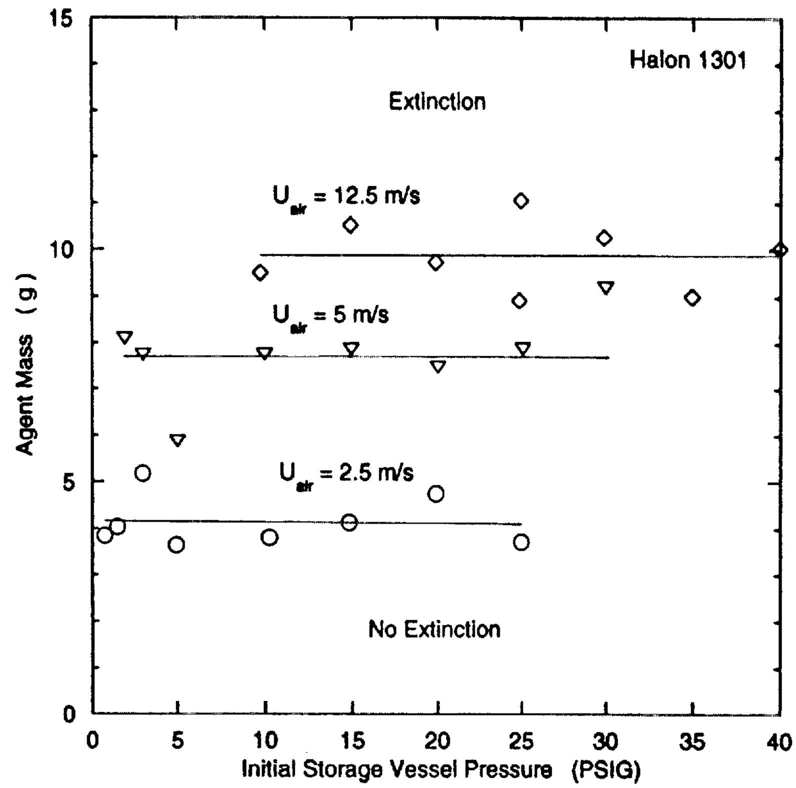

Fig. 5 Extinction limits of step-stabilized methane flames: agent mass vs. initial vessel pressure.

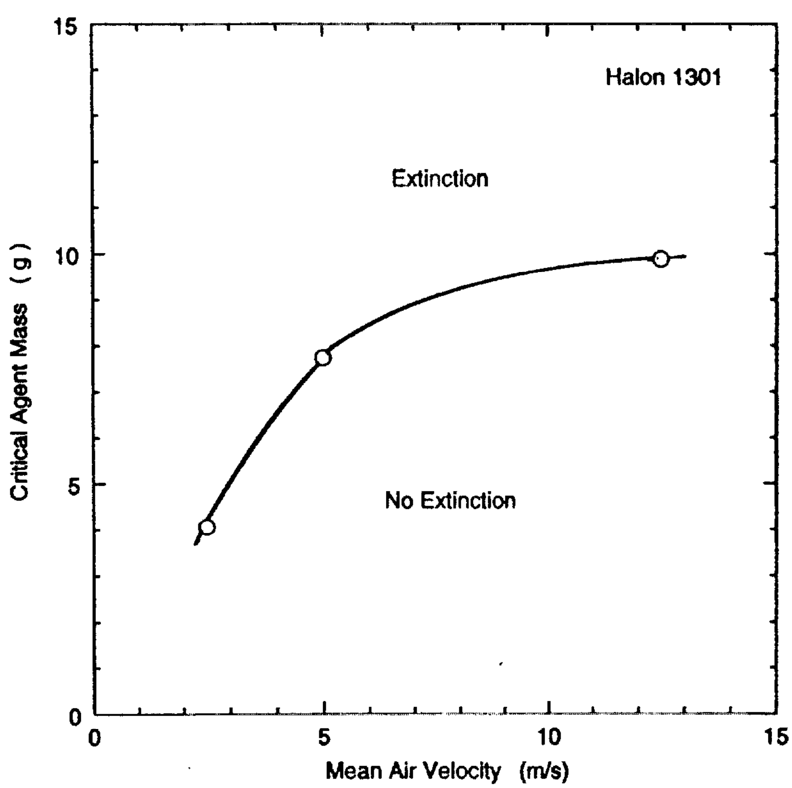

Fig. 6 Extinction limits of step-stabilized methane flames: critical agent mass vs. mean air velocity.